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Slope Dependent Morphometric Analysis as a Tool Contributing to Reconstruction of Volcano Evolution

Veronika Kopačková, Vladislav Rapprich, Jiří Šebesta and Kateřina Zelenková
Czech Geological Surve
Charles University in Prague,
Faculty of Science, Department of Applied Geoinformatics and Cartography
Czech Republic

1. Introduction

People have been fascinated by volcanoes since time immemorial. This is mainly due to the serious consequences that volcanic eruptions represent for human society. Volcanic activity develops in various ways. Therefore, evolutionary trends and the history of the volcanic system should be well understood when future hazards must be predicted and their impact on human society reduced. A volcano's history can be reconstructed from its deposits, their superposition and spatial relationships. Geological mapping is the crucial method for acquiring this information. Unfortunately, large areas in volcanic zones are inaccessible for research directly in the field. In these areas, the geological setting must be investigated by a combination of remote sensing methods and field observations from accessible outcrops.

Surface methods such as remote sensing and morphological analysis provide fast and relatively cheap information, complementary to classical field geology for studying the subsurface geology. These methods can be beneficial, especially for areas with poor accessibility and/or dense vegetation cover. Volcanoes or volcanic complexes quite often represent such areas. Land forms are a result of geologic and geomorphologic processes that occur on the earth's surface thus land forms are not chaotic, but have been structured by geologic and geomorphologic processes over time. The geomorphology of volcanic formations as a whole seems to be a reflection of the underlying geology with steep-sided land forms occurring at each of the "strong" rock units and long, with gentle slopes and topographic breaks found on „soft" rocks. To support this theory, we employed and tested new methodology combining information arising from field surveys together with visual interpretation and statistical spatial analysis of morphometric slope-depending classes to define the spatial extent of various volcanic formations and to identify major tectonic phenomena from features derived from the geomorphology in more accurate way.

2. Study areas

Morphometric analysis was applied to two case study areas, two volcanic complexes of distinct geotectonic setting, age and volcanic evolution. Selected volcanic areas encompass a number of features and rock types associated with volcanic activity. The first case study was carried out in the Conchagua Volcanic Complex, El Salvador (Central America), while the second one was performed in the Doupovské hory Volcanic Complex, Czech Republic (Central Europe).

2.1 Conchagua Volcano

The Pacific coast of Central America is bordered by a chain of active subduction-related volcanoes. This chain is called the Central American Volcanic Arc (CAVA) and extends from Guatemala via El Salvador, southern Honduras, Nicaragua and Costa Rica to western Panama (e.g., Carr et al., 2003). The volcanic arc is associated with the subduction of the Cocos plate beneath the Caribbean plate and it is divided into several segments by traverse faults. Conchagua Volcano is located near one of these segment boundaries (Carr, 1984).

Conchagua Volcano (Fig. 1), on which our research has been focused, is the easternmost volcano of the Salvadorian mainland. Conchagua volcano is located on the Conchagua Peninsula surrounded by the Pacific Ocean and the Gulf of Fonseca. The area of the Gulf of Fonseca including the Conchagua Peninsula is characterized by the presence and intersection of three important tectonic structures. The Median Trough (syn. Salvadorian Depression called the Nicaraguan Depression further to the SE) is parallel to the Middle America Trench. The Trough originated in response to extension related to the subduction roll-back of the Cocos Plate (Phipps–Morgan et al., 2008; Funk et al., 2009). The tension on oblique subduction is accommodated by dextral strike-slip movements on the El Salvador Fault Zone (the northern edge of the Salvadorian Depression - Corti et al., 2005). Extension related to eastward escape of the Chortis Block is thought to be the main reason for formation of the Comayagua Graben (Burkart & Self, 1985). The Guayape Fault running from the Gulf of Fonseca to the northeast (Finch & Ritchie, 1991) is interpreted as a Mesozoic terrane boundary, originally being part of the Guayape–Papalutla Fault Zone (Silva–Romo, 2008). Early studies assumed sinistral movement on the Guayape Fault (Burkart & Self, 1985), but sinistral displacement exceeding 50 km was documented by Finch & Ritchie (1991). The latter authors have also observed several dextral strike-slip basins providing evidence for a later dextral movement phase. Dextral movements on this fault may result from anticlockwise rotation of the Chortis Block (Gordon & Muehlberger, 1994).

The eruptive history of the Conchagua Peninsula has been recently reconstructed by Rapprich et al. (2010). The oldest rocks cropping out in this area are Playitas welded rhyolitic ignimbrites of Miocene age. The next stage is represented by non-welded pyroclastic deposits of La Unión unit (mean K–Ar age: 13.3 ± 3.7 Ma). The presence of banded pumice, deposits containing both mafic scoria and felsic pumice fragments is interpreted as being a result of mingling between basaltic and dacitic magmas. Eruptions of this unit were most likely triggered by injection of basaltic magma into a dacitic magma chamber. Rocks of the subsequent Pozo unit are poorly exposed and strongly altered. Andesite lavas alternate with mafic pyroclastic flow deposits. As the non-welded pyroclastic and strongly altered effusive and pyroclastic rocks have similar surface features, the products of these two phases were combined in this study. Subsequent activity became much calmer and was predominated by effusions of basaltic andesite to andesite lavas. The lava sequences were subdivided into two formations in relation to their geochemical constraints (Rapprich et al., 2010). The earlier of the two formations, Pilón Lavas, were dated at 8.4 ± 1.2 Ma (Quezada & García, 2008), whereas the younger lavas of Pre-Conchagua – Juana-Pancha were dated at 1.6 ± 0.6 to 1.3 ± 0.4 Ma (Quezada & García, 2008; Rapprich et al., 2010). Identical physical properties make these two formations indistinguishable on the basis of their morphology. Hence, both lava formations were combined for the purpose of this study. The volcanic evolution terminated with the formation of two subsequent composite scoria cones in the Pleistocene (0.15 ± 0.02 and 0.41 ± 0.1 after Quezada & García, 2008). Similar physical properties led us again to combine the two cones in a single unit. Since the Pleistocene, the complex has been quiet in terms of volcanic eruptions, but the volcanic forms have been modified by erosion and post-volcanic tectonics. Tectonic depressions were filled with sediments and distal ash-fall during the Holocene. The most prominent ash layer in these depressions is white in colour and has rhyolitic composition. It is interpreted as distal fallout of the Tierra Blanca Joven eruption of the Ilopango Caldera (Rapprich et al., 2010).

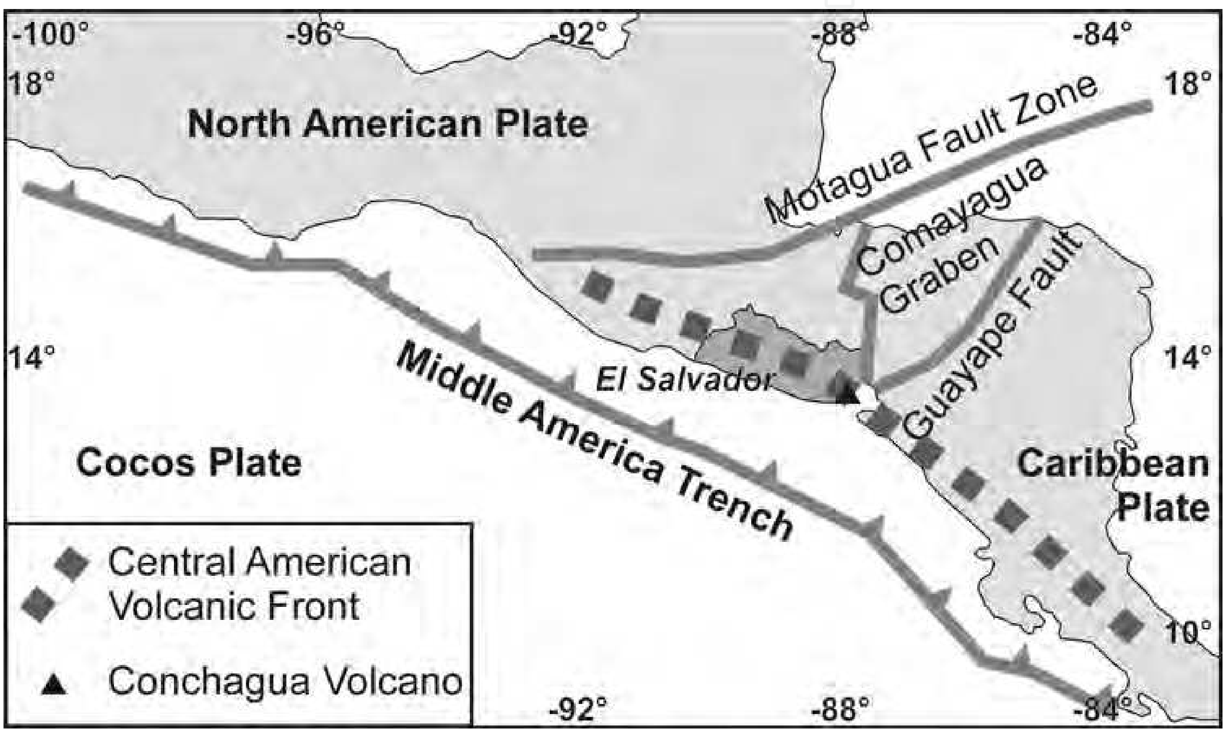

Fig. 1. Location of the Conchagua Volcano - black triangle

2.2 Doupovské hory Volcanic Complex

The Dopovské hory Volcanic Complex (DHVC) belongs to a system of Cenozoic intra-plate volcanic/magmatic complexes in Central-Western Europe (e.g., Lustrino & Wilson, 2007). Similarly to other Cenozoic volcanic complexes in Central-Western Europe, the magmas of the DHVC can be classified as within-plate alkaline in character and were derived from the sublithospheric mantle.

The DHVC is located in the western part of the Eger Graben, which is the easternmost branch of the European Cenozoic Rift System (ECRIS, Dèzes et al., 2004). The Eger Graben runs across the north-western part of the Bohemian Massif in the ENE–WSW direction (Fig. 2), roughly following the Variscan suture between the Saxothuringian and Teplá–Barrandian domains of the Bohemian Massif (Babuška et al., 2010; Mlčoch & Konopásek, 2010). It is interpreted as an incipient rift structure formed during two distinct extensional phases (Rajchl et al., 2009). The Late Eocene to Early Miocene phase was characterised by

NNE–SSW to N–S oriented horizontal extension, oblique to the rift axis. The palaeostress field of this phase as well as OIB-like magmatism within the Eger Graben most probably reflected lithospheric doming due to thermal perturbation of the astenosphere (Dèzes et al., 2004). Later, lithospheric folding in the Alpine–Carpathian foreland and stretching along the crest of a growing regional-scale anticlinal feature resulted in an orthogonal extensional phase (Dèzes et al. 2004; Bourgeois et al. 2007; Rajchl et al. 2009).

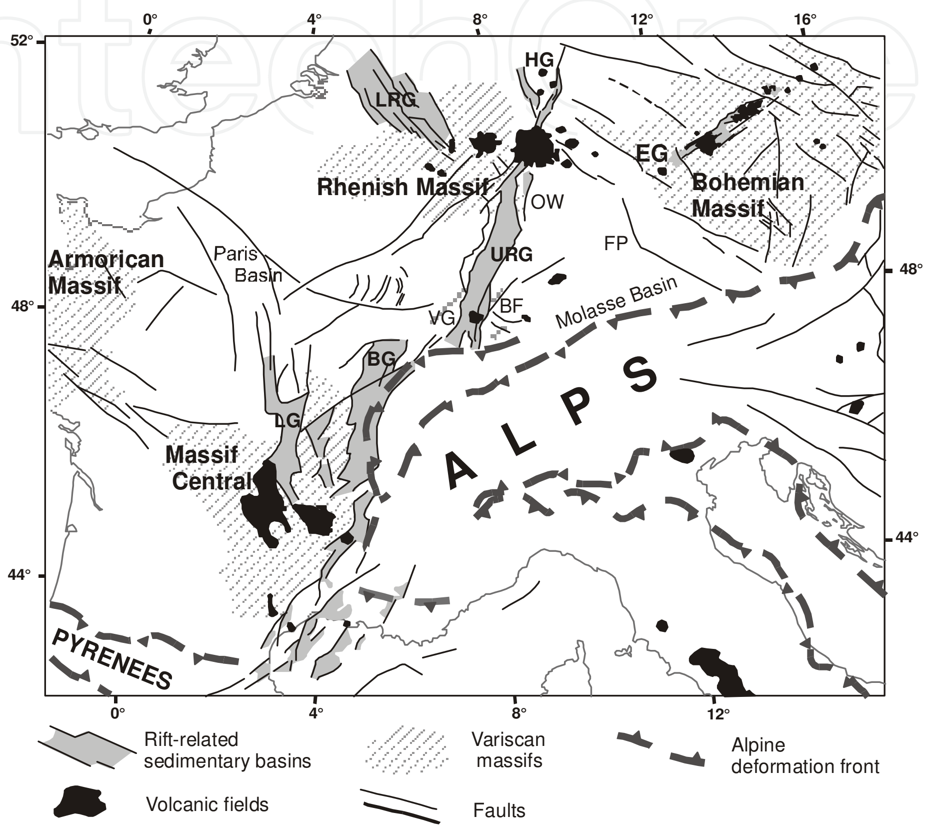

Fig. 2. Location of the Doupovské hory Volcanic Complex within the ECRIS (after Dézes et al., 2004)

Several geological units meet in the basement of the DHVC in the form of a heterogeneous crustal mosaic (Mlčoch & Konopásek, 2010; Valenta et al., 2011). Paragneisses, felsic granulites, orthogneisses, mica schists, and phyllites of the Saxothuringian Unit extend from the north in the basement of the DHVC. Variscan Nejdek–Eibenstock granitic pluton plunges beneath the DHVC from the west. Gneisses, micaschists and phyllites of the Teplá–Barrandian Unit form the basement to the south. Amphibolites, eclogites and peridotites (equivalent to the Mariánské Lázně Complex) occur beneath the central part of the DHVC. The south-eastern sector of the DHVC (delimited by the Střezov and Liboc faults) is underlain by an up-to-800 m-thick sequence of Late-Palaeozoic sedimentary rocks covering the Teplá–Barrandian Unit basement.

The Doupovské hory Volcanic Complex was formerly interpreted as a huge stratovolcano (e.g., Zartner, 1938; Kopecký, 1988). However, voluminous pyroclastic material was produced only during the early stages of the volcanic evolution (Hradecký, 1997). Volcaniclastic material of subsequent phases was not produced by explosive activity. The volcanic evolution of the DHVC started in the very Early Oligocene with eruptions of

Strombolian and phreatomagmatic types. These eruptions buried the fauna of mammal zone MP-21 (Fejfar & Kaiser, 2005), which facilitated dating of this initial phase. Up to 80 m of pyroclastic deposits were produced during the Early Oligocene eruptions. Effusive activity soon predominated over volcanic explosions. The lavas emitted from a set of subsequent shield volcanoes separated from one another by phases of volcano edifice decay. The complex consists of alkaline volcanic rocks, namely foidites, basanites and tephrites. Weak erosion preserved superficial products dominated by sequences of gently dipping mafic lavas with subordinate concomitant volcaniclastics (Rapprich & Holub 2008). The subvolcanic rocks are exposed on a small area in the central part of the DHVC (Holub et al., 2010; Haloda et al., 2010). The activity terminated in the Early Miocene when several small monogenic volcanoes were formed on the northern periphery of the complex (Sakala et al., 2010).

3. Data and methods

3.1 Introduction to morphometric analysis

Automatic methods of analyzing DEM have been increasingly used in geomorphological (Dikau et al., 1989; Kaab et al., 2005; Hancock et al., 2006) and morphotectonic research (Jordan et al., 2005). A quantitative technique for analysis of land surface parameters is known as morphometry / geomorphometry. In simple terms, morphometry aims at extracting (land) surface parameters (e.g., morphological, hydrological) and objects (watershed, stream networks, landforms) using a set of numerical characteristics such as slope, profile curvature, plan convexity, cross-sectional curvature minimum and maximum curvature derived from DEM (Wood, 1996; Pike, 2000; Fisher et al., 2004). Landform and lithological units differ in their geotechnical properties (e.g., rock strength) and in the degree of weathering and rock disorganisation resulting from diverse erosion processes; therefore, they display statistically significant compositional differences with respect to their proportions of morphometric classes. Morphometric analysis can provide unique information that can be linked to land erosion conditions, landform characteristics, morphologic and tectonic evolution. Various approaches have been employed to link morphometry with the geomorphological and volcanological conditions (Ganas et al., 2005; Bolongaro-Crevenna at al., 2005; Liffton et al., 2009; Passaro et al., 2010; Altin & Altin, 2011).

3.2 DEM inputs

For both case study areas, comparable elevation data were utilized and later processed in the same way. Vector topographic base maps on a scale 1:25,000 (Servicio Nacional de Estudios Territoriales, SNET and the military topographic maps called DMÚ25) were used to reconstruct the Conchagua and Doupovské hory volcanic complexes. A Digital Elevation Model (DEM) has been prepared from vector contours at 10 m intervals from the 1:25 000 topographic map, interpolated and resampled to 5x5 m^2 pixel size.

3.3 DEM data processing

In morphometric approaches, the first and second order derivatives of DEM’s are the key components which can be related to geomorphological features and processes. While Evans (1972) separated curvatures into two orthogonal components (e.g., profile and plane curvature), Wood (1996) proposed an algorithm for measures of the surface convexity/concavity. As a result, one component, the cross sectional curvature, is calculated instead of the profile and plane curvature components. This parameter is computed in a more simple way and can be directly linked to geomorphological phenomena. Like Evan's profile and plane curvatures, this parameter can be calculates as long as the slope differs from zero (slope=0, the cross-sectional curvature (crosc) and longitudinal curvature (longc) remain undefined). In these cases, two alternative measures of the convexity (e.g., minimum and maximum curvatures) are determined. To calculate the morphometric features, a local window passes over the DEM and the changes in the gradient of a central point in relation to its neighbors are extracted using the approximations given in Table 1.

Morphometric parameter	**Approximation**
Slope	arctan (sqrt ($d^2 + e^2$))
Cross-sectional curvature	$n * g * (a * x^2 + by^2 + cxy + dx + ey + f)$
Maximum curvature	$n * g * (-a - b + \mathrm{sqrt}((a - b)^2 + c^2))$
Minimum curvature	$n * g * (-a - b - \mathrm{sqrt}((a - b)^2 + c^2))$

Table 1. DEM pixel size; n: local window size; x,y: local coordinates; a-f: quadratic coefficients.

Based on the DEM derivatives specified above, Wood defines a set of criteria (e.g., slope, cross-sectional curvature, maximum and minimum curvature) to identify morphometric classes (Tab. 2). For features with positive values (+) of the slope, the cross sectional curvature should be considered and, for features with zero slope value (0), the cross section curvature is undefined (x) and the maximum and minimum curvatures become to be the main classification criteria.

We constructed the morphometric maps utilizing Wood's algorithm. First, the algorithm was used pixel by pixel to calculate the topographic slope and the maximum and minimum convexity values. Then, for each pixel, the variation in these parameters was quantified with respect to neighboring pixels (in orthogonal directions), and then, based on a set of tolerance rules (Tab. 2), each pixel was assigned to one of six possible elemental forms or morphometric classes: ridge, channel, plane, peak, pit and pass.

Wood's algorithm offers the option of parametrizing the relief on the basis of changes in the tolerance of the topographic slope and convexity for assigning to morphometric classes. Slope change tolerance values are used to decide if a pixel qualifies as a peak or a pit, whereas convexity tolerance values are used to determine if a pixel has enough curvature to qualify as a channel or a ridge.

The constructed model was calibrated by running the algorithm with slope tolerance values varying between 0.3 and 3.5 and convexity tolerance values set from 0.001 to 1.000. The resultant morphometric classes were color-coded and visualized; the best result was achieved by draping the color-coded morphometric classes over a three-dimensional (3D) map formed by the fusion of an altitudinal map using ArcGIS 3D Analyst SW. The best fit occurred with slope tolerance values of 3.0 and convexity tolerance values of 0.02.

The relationship was assumed to exist between a geotechnical property of the studied rock formations and the slope angles. Additionally, a systematic break in the slope angles matching the elevation change across tectonic features (e.g., faulting, fracture jointing) could be observed (Gamas et al., 2005). To test the feasibility of linking the geomorphological and tectonic features with the morphometric features classified into defined classes based on their steepness (slope degree), a new product, a slope-dependent morphometric map, was constructed.

Morphometric Feature	**Description**	**Slope**	**Cross-sectional curvature**	**Maximum curvature**	**Minimum curvature**
Peak	Point that lies on a local convexity in all directions (all neighbours lower).	0	x	+va	+va
Ridge	Point that lies on a local convexity that is orthogonal to a line with no convexity/concavity.	0	x	+va	0
		+va	+va	*	*
Pass	Point that lies on a local convexity that is orthogonal to a local concavity.	0	x	+va	-va
Plane	Points that do not lie on any surface concavity or convexity.	0	x	0	0
		+va	0	*	*
Channel	Point that lies in a local concavity that is orthogonal to a line with no concavity/convexity.	0	x	0	-va
		+va	-va	*	*
Pit	Point that lies in a local concavity in all directions (all neighbours higher).	0	x	-va	-va

Table 2. Classification criteria for morphometric features (modified from Wood): va: derivative values, x: undefined value, *: not a part of the selection criteria.

For the Conchagua volcano, a thematic raster was created from the DEM by grouping the slope values together into six classes: class 1: flat terrain (inclination < 5°), class 2: very low-steep slopes (inclination 5 – 10°), class 3: low-steep slopes (inclination 10 – 15°), class 4: moderate-steep slopes (inclination 15 – 20°), class 5: steep slopes (inclination 20 – 25°) and class 6: very steep slopes (inclination > 25°). The topography of the Doupovské hory volcanic complex does not exhibit such high altitudes and flat to moderate slope terrain is characteristic for this area rather than steep slopes; therefore the slope values were classified into four classes as follows: class 1: flat terrain (inclination < 5°), class 2: very low-steepness slopes (inclination 5 – 10°), class 3: low-steepness slopes (inclination 10 – 15°), class 4: moderate- high steepness slopes (inclination >15°).

In order to classify the areal morphometric classes (ridge, plane, peak, pit and pass) with respect to the slope gradient, a matrix analysis was applied. Matrix analysis produced a new thematic layer (matrix of 6x6 classes for the Conchagua and 6x4 classes for the DHVC, respectively) that contained a separate class for every coincidence of selected classes in the morphometric map (e.g., peak, ridge, pass, plane, channel, pit) and also a thematic slope map (slope classes 1-6 and 1-4, respectively). As result, maps classifying the six morphometic features according to the slope gradient of the relief from flat to very steep peaks, ridges, passes, channels, planes and pits were constructed.

3.4 Interpretation and further geostatistical analysis

Slope-dependent morphometric maps calculated for the both test sites were correlated with the available geological maps. Visual analysis of the spatial occurrence of the newly derived morphometric parameters within the diverse litho-stratigraphic formations of the Conchagua Volcanic Complex, El Salvador (e.g., La Union pyroclastic deposits versus mafic lavas) and the Doupovské hory Volcanic Complex, Czech Rep. (e.g., lahar deposits versus lavas) clearly showed that a spatial distribution (pattern) of these morphometric features reflects variations in the rock strength, resistance, tectonics, and volcanic topography. As result, the morphometric map became a basis for delineating major geomorphological entities (Figs. 4, 10).

Zonal statistics analysis was employed to study the morphometric pattern and its statistical differences within the geomorphologic units. Zonal functions were used to compute an output dataset, where for each zone (in our case each morphologic unit) the following statistical variables were computed based on the morphometric feature values of the cells, on their location and the association that the location has within a geomorphological zone: i) MAJORITY — Determined the value that occurred most often of all the cells in the input dataset (morphometric map) that belonged to the same zone (morphological unit); ii) MINORITY — Determined the value that occurs least often of all the cells in the input dataset (morphometric map) that belonged to the same zone (morphological unit); iii) MEDIAN — Determined the median value of all the cells in the input dataset (morphometric map) that belonged to the same zone (morphological unit).; iv) VARIETY — Calculated the number of unique values for all the cells in the input dataset (morphometric map) that belonged to the same zone (morphological unit).

4. Results

The morphometric spatial pattern of each geomorphological entity was assessed; frequency graphs showing the abundance of the morphometric matrix classes within each geomorphological unit are given in Figs. 8 and 13. The results from the zonal statistics are depicted in Figs. 9 and 14. In both study areas, the peaks and passes showed none or very sparse (minor) abundance thus cannot be distinguished either in the morphometric maps or in the frequency charts.

4.1 Conchagua Volcano

The morphometric analysis produced an image enhancing different morphologies in the area of Conchagua Volcano (Fig. 4). The loose, non-welded pyroclastic deposits display high variability of morphometric features resulting from the intense erosion (grooves) of ephemeral streams. The hard rocks have significantly more equable morphology with short steep slopes defining the fronts of lava flows or even lava lobes.

Six distinct morphologies were identified in the area of the Conchagua volcano (Fig. 4). Flat surfaces (slope < 5°) predominate in welded rhyolitic ignimbrites (I), non-welded pyroclastic and altered volcanic rocks (II), and monogenetic cone lithologies (V). However, these lithologies still contain such morphometric features as ridges and channels. Holocene post-volcanic sediments (VI) have overall aligned smooth relief with slope of < 5°; very steep slopes (ridges) are encountered least frequently.

In rhyolitic ignimbrits (I), the ridges and channels characterize margins of welded ignimbrite exposures, whereas the surface of these resistant rocks creates flat plains. The channels result partly from tectonic disturbances of the oldest rock sequence and also from prolonged erosion. On the other hand, the sturdiness of these rocks prevents the edges of channels and ridges from being smoothed down. Consequently, ridges and channels with low slopes occur only rarely.

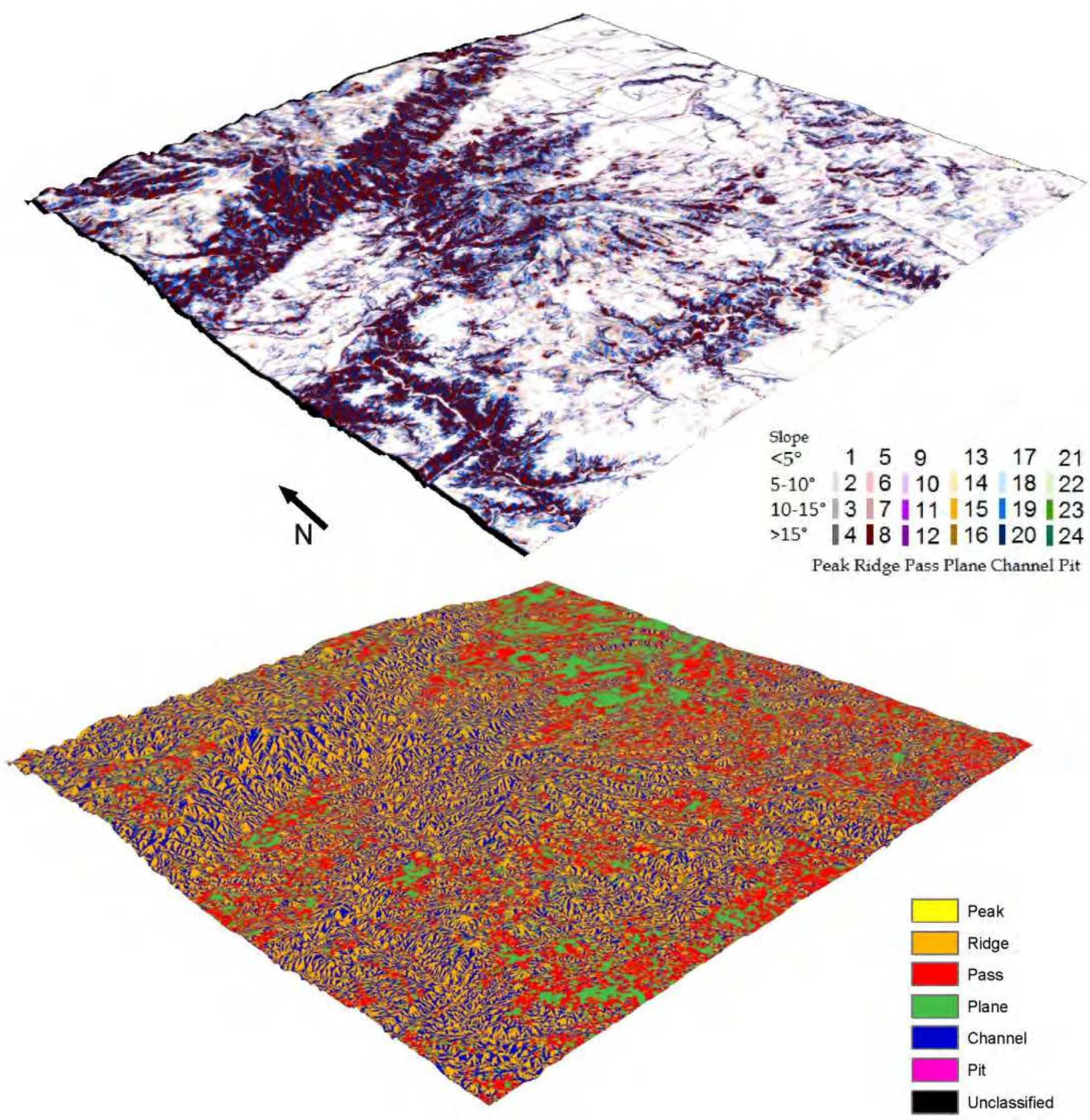

Fig. 3. DHVC: The morphometric map (lower layer) and its derived product: slope-dependent morphometric map (upper layer).

Different compositions of morphological features characterize the Miocene non-welded pyroclastic and altered sequences of lavas (II) alternating with pyroclastics. All landforms were easily smoothed down by erosion. Low-angle dipping planes, ridges, passes and channels strongly dominate over steep-slope forms (Figs. 4, 8).

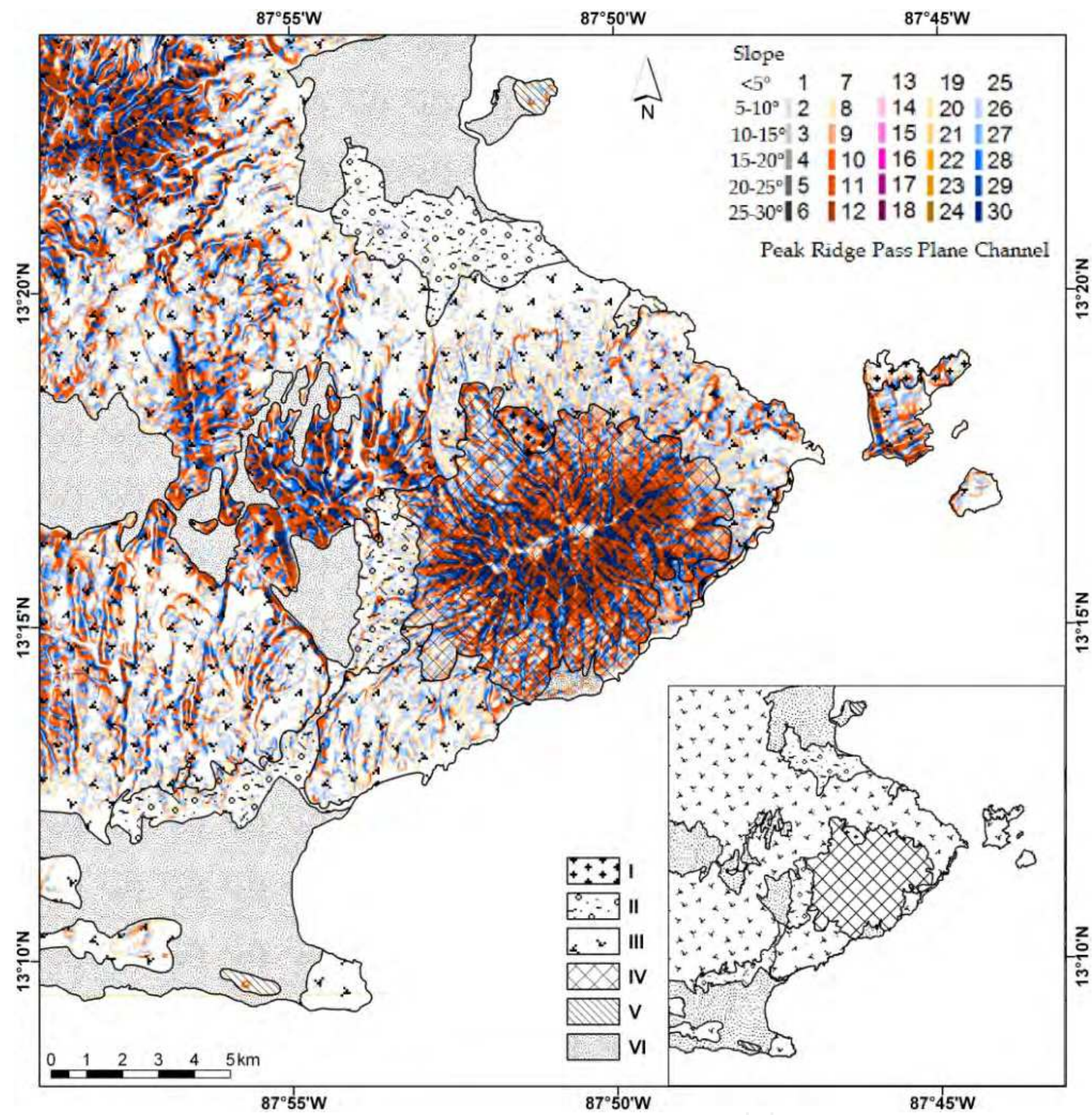

Fig. 4. Morphometric map and morphological units: I – welded rhyolitic ignimbrites; II – non-welded pyroclastic and altered volcanic rocks (Miocene); III – lava sequences (Miocene to Pliocene); IV – composite scoria cones (Pleistocene); V – monogenetic cones (Pleistocene); VI – post-volcanic sediments (Holocene).VI – post-volcanic sediments (Holocene).

The lava sequences of Miocene to Pliocene age (III) dip gently from the source vents; therefore, in contrast to the lithologies described above, the lava sequences have a characteristic flat terrain while short, low to moderate steep and steep ridges and channels characterize the lava flow fronts and sides (Fig. 4). The traverse section of a typical lava flow is concave and the steep sides of the lava continuously pass into a plateau at the top of the lava. The morphology of the lavas combines planes with ridges and channels of variable steepness. The resistance of the (basaltic) andesite lavas against common erosion preserves the original morphology long after the lava emplacement. Hence the lava-front can still be identified in the morphometric map (Figs. 4, 5).

The Conchagua Volcano (IV), i.e. both its cones Ocotal and Banderas, are characterized by very steep (> 25°) to moderate-steep (15°-25°) ridges with a dense network of erosion very steep (> 25°) to moderate-steep (15°-25°) grooves represented in the morphometric map as channels (Figs. 4, 8). The majority and median (Fig. 9) point of the same morphometric feature - ridges with very steep slopes, flat (slope < 5°) passes are the least frequent. This distinctive morphology, where very steep to steep slopes are predominant is clearly visible in the field, topographic maps, DEM and this observation is sufficiently confirmed by numerical evaluation of morphometric analysis. Steeply inclined channels and ridges distinctly predominate over low-angle landforms. Bimodal distribution of morphometric classes (Fig. 8.) is characteristic for this unit.

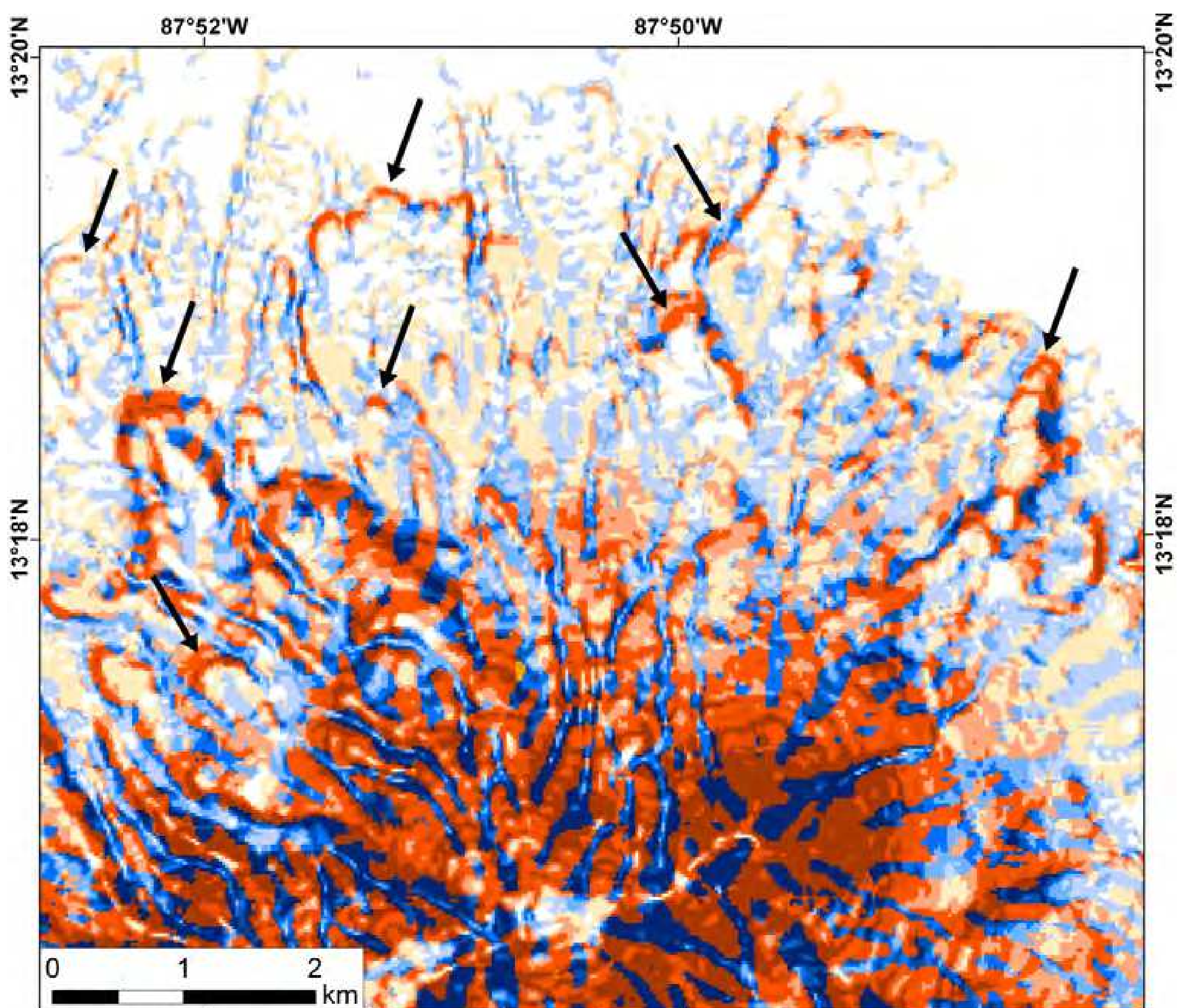

Fig. 5. Detail of the lava flow fronts (black arrows) from the slope-dependent morphometric map.

The monogenetic volcanic cones (V) did not produce a prominent morphology. Consisting of non-welded pyroclastic deposits, the volcanic forms are characterized by morphological composition comparable with Miocene non-welded pyroclastics and altered volcanic rocks. Planes are combined with low-angle, inclined ridges and channels.

Several tectonic depressions are associated with N-S to NNE-SSW trending faults filled with post-volcanic sediments and distal ash fall-out deposits (VI). Sedimentation strongly outweighs erosion in these areas and sediments level the surface. The morphology is therefore dominated by horizontal planes and low-angle structures.

Fig. 6. Dense network of erosion grooves on the Ocotal (centre and right) and Banderas (to the left) cones of the Conchagua Volcano.

Fig. 7. Post-volcanic sediments and distal ash fall-out deposits from 130 km distant Ilopango Caldera filling up the tectonic depressions.

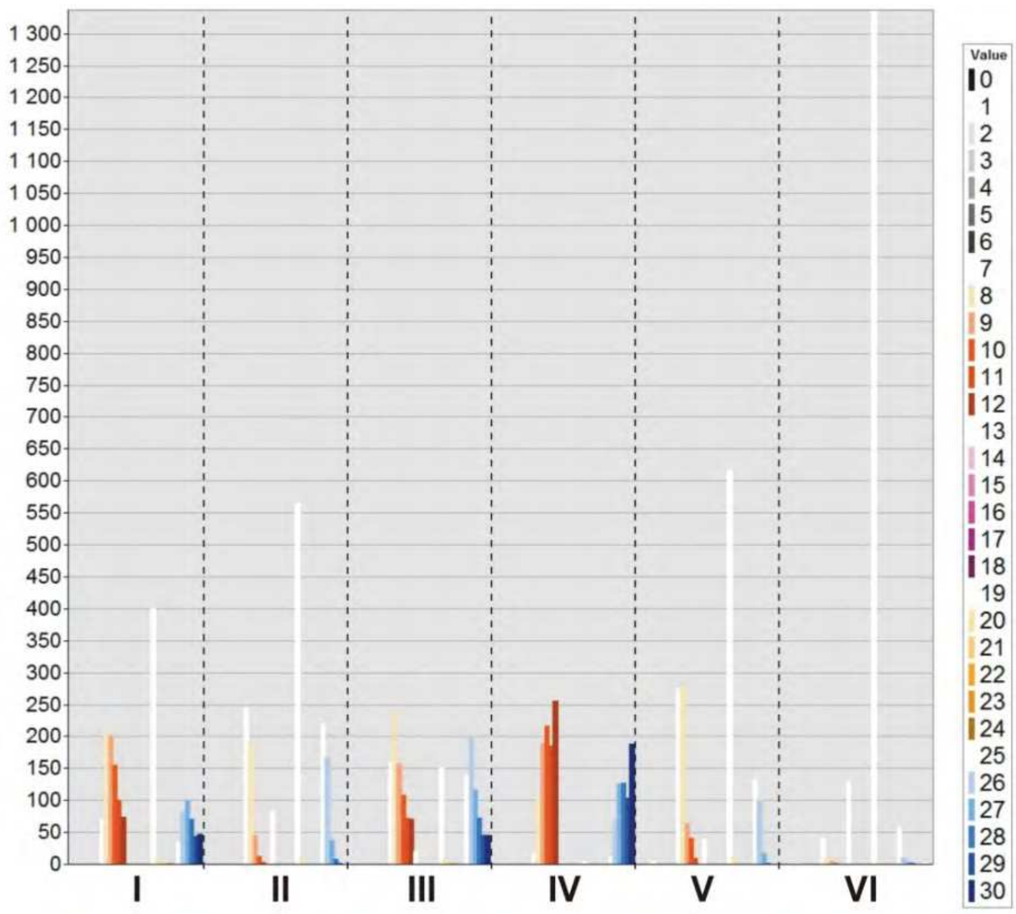

Fig. 8. Frequency of morphometric classes within the defined geomorphological features normalized by the areal extent of the geomorphological features. Pits were not identified.

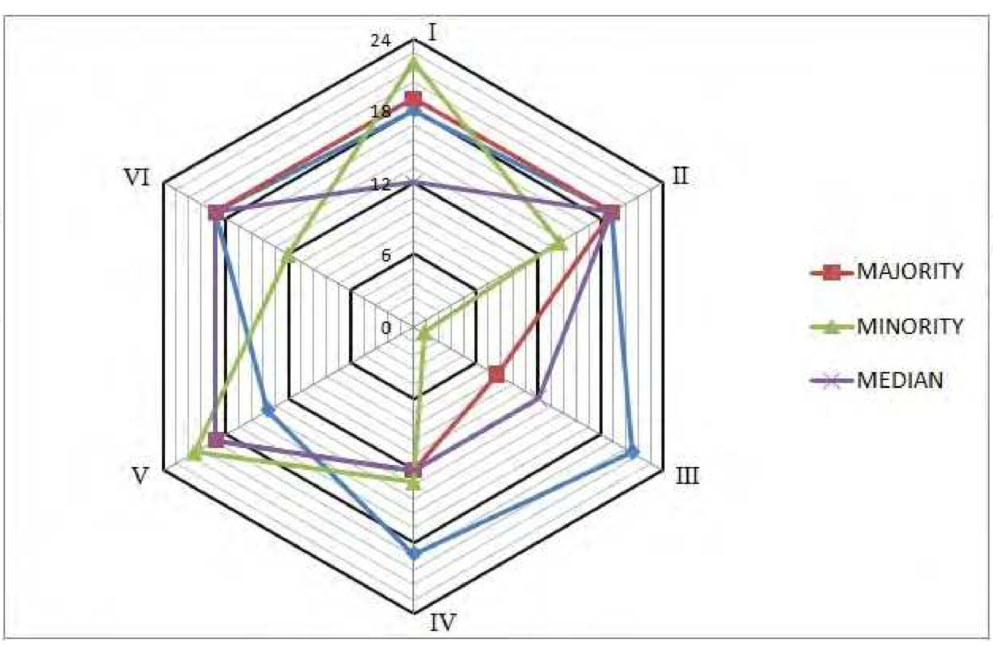

Fig. 9. Conchagua volcano: Graph showing the zonal statistics parameters for the six principal geomorphological units.

4.2 Doupovské hory Volcanic Complex

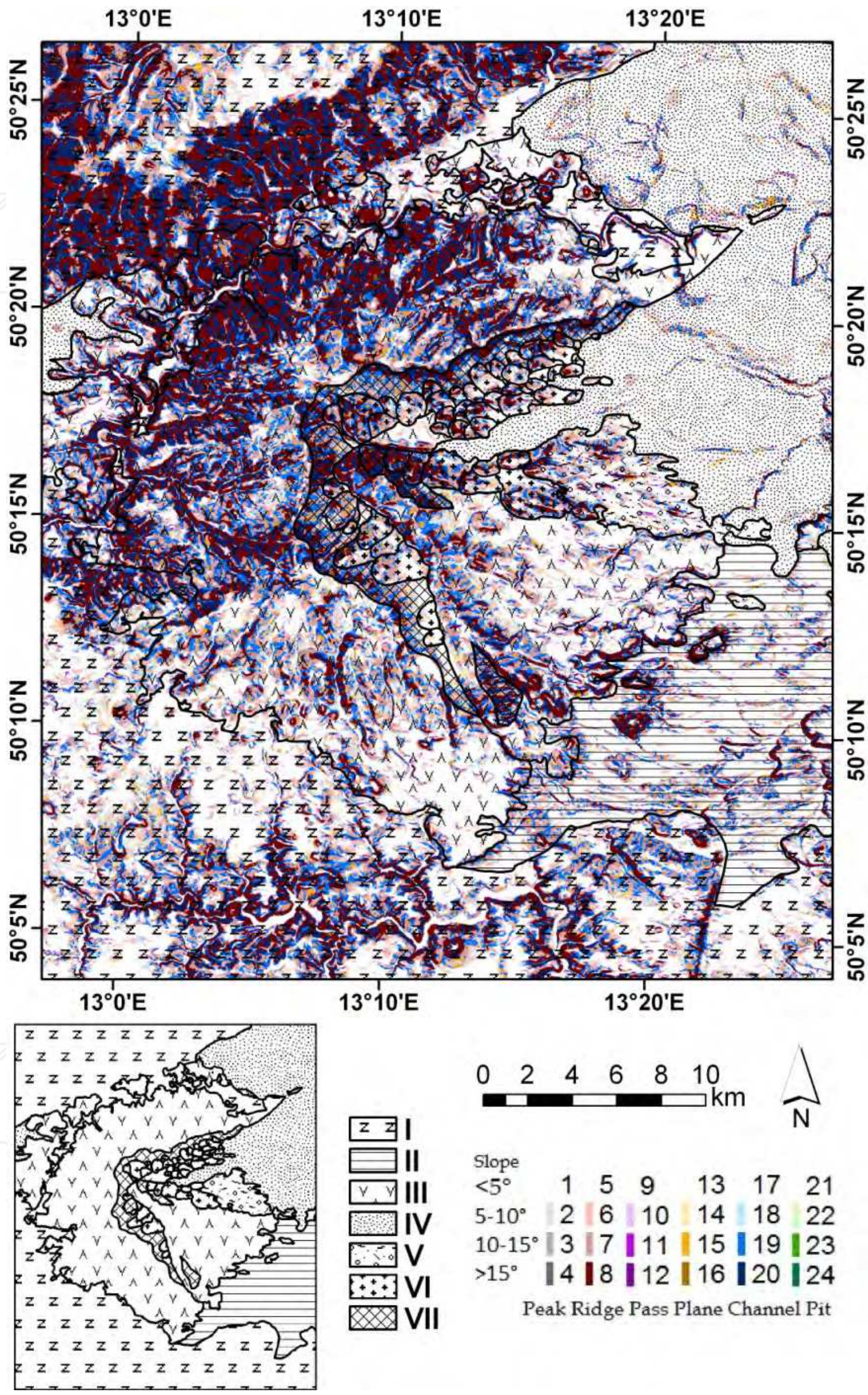

Fig. 10. I – Basement of Crystalline rocks; II – pre-volcanic sediments (Permo-Carboniferous); III – Lava sequences of the DHVC; IV – post-volcanic sediments (Miocene); V – lahar sequences; VI – diastrophic blocks (4, diastr_block); VII – fault scarp.

The area of the Doupovské hory Volcanic Complex exhibits seven principal geomorphological units comparing the geomorphological results with the geological data. (Fig. 10). The basement of the DHVC (I) is built of crystalline rocks, namely granites, gneisses, shists and metabasic rocks. These rocks are resistant to erosion and this is reflected in the morphology, which therefore contains extensive planes, as a peneplenized pre-volcanic landscape, combined with steep-sided gorges cut into these plateaus. These canyons are characterized by unsmoothed edges and therefore low-angle ridges and channels are in a minority compared to steeply inclined ones. The flat relief is locally disturbed by isolated remnants of scattered monogenetic volcanoes penetrating through the metamorphic rocks (Fig. 10).

Fig. 11. Small isolated volcanic bodies rising above the flat relief on crystalline rocks south of the DHVC.

Fig. 12. Lava sequences of the DHVC form tabular rocks with flat apical plateaus.

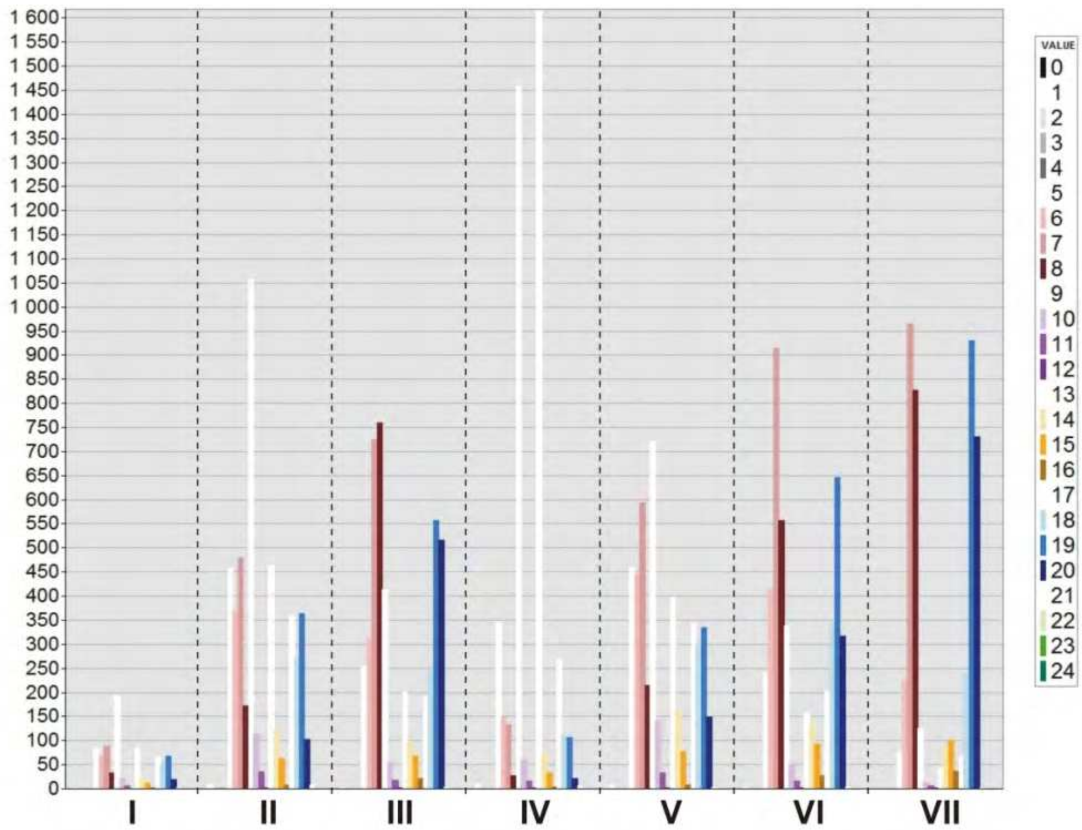

Fig. 13. DHVC: Frequency of morphometric classes within the defined geomorphological features normalized to the areal extent of the geomorphological feature. Pits were identified but had a minor occupancy.

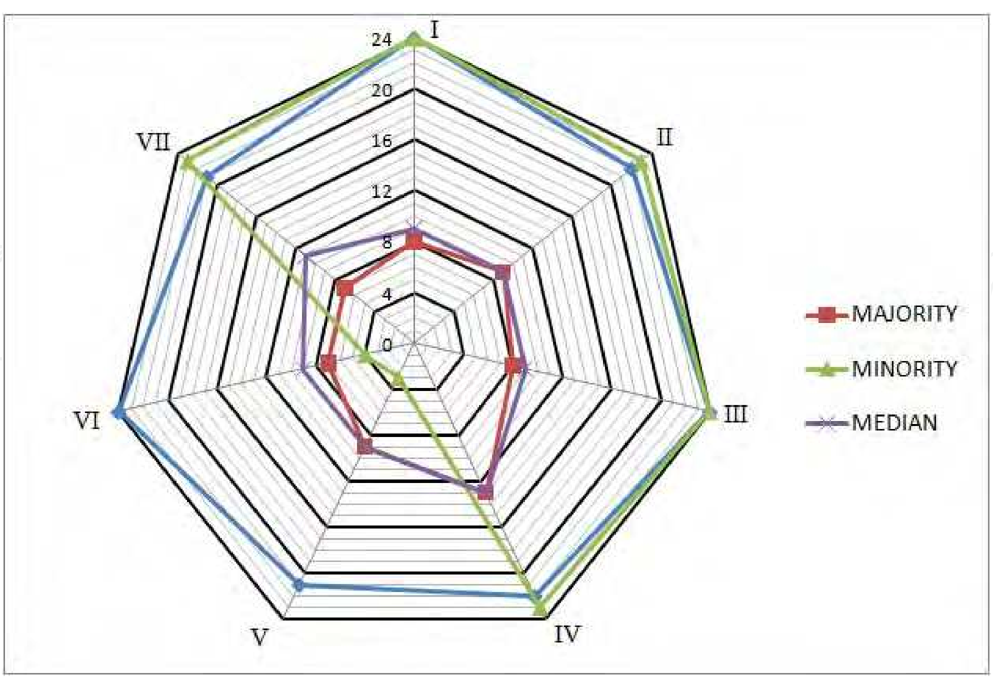

Fig. 14. DHVC: Graph showing the zonal statistics parameters for the seven DHVC principal geomorphological units.

Pre-volcanic sediments (II) represented by Permo-Carboniferous siltstones, sandstones and conglomerates created part of the flat, pre-volcanic morphology. The most frequent morphometric class is a flat slope (< 5°) ridge. In contrast to crystalline rocks, the sediments are much more prone to erosion. Valleys cut into these rocks do not have such steep walls and sharp edges, as these are effectively smoothed down by erosion of the soft rocks. Consequently, deep valleys and pronounced ridges with steep walls occur rarely in areas formed by these rocks. On the other hand, gently dipping channels and ridges are frequent as are planes.

The proper Doupovské hory Volcanic Complex consists of lava sequences (III) displaying flat, weakly periclinally inclined relief hold by structural surfaces of lava flows. Steep (most freuqeunt) to moderate ridges and channels create a characteristic morphometric pattern. The morphology can be readily compared with the results observed on lava sequences in the area of the Conchagua Volcano. The margins of the lava plateaus combine gentle and steep channels and ridges, whereas the surface of the lavas is characterized by horizontal to gently dipping planes.

The areas of post volcanic (Miocene) sediments (IV) are characterized by sedimentation prevailing over erosion. Therefore, these areas are dominated by flat low-angle (<5°) forms, namely planes whereas steep-sided ridges and channels are only occasionally represented by a few river valleys.

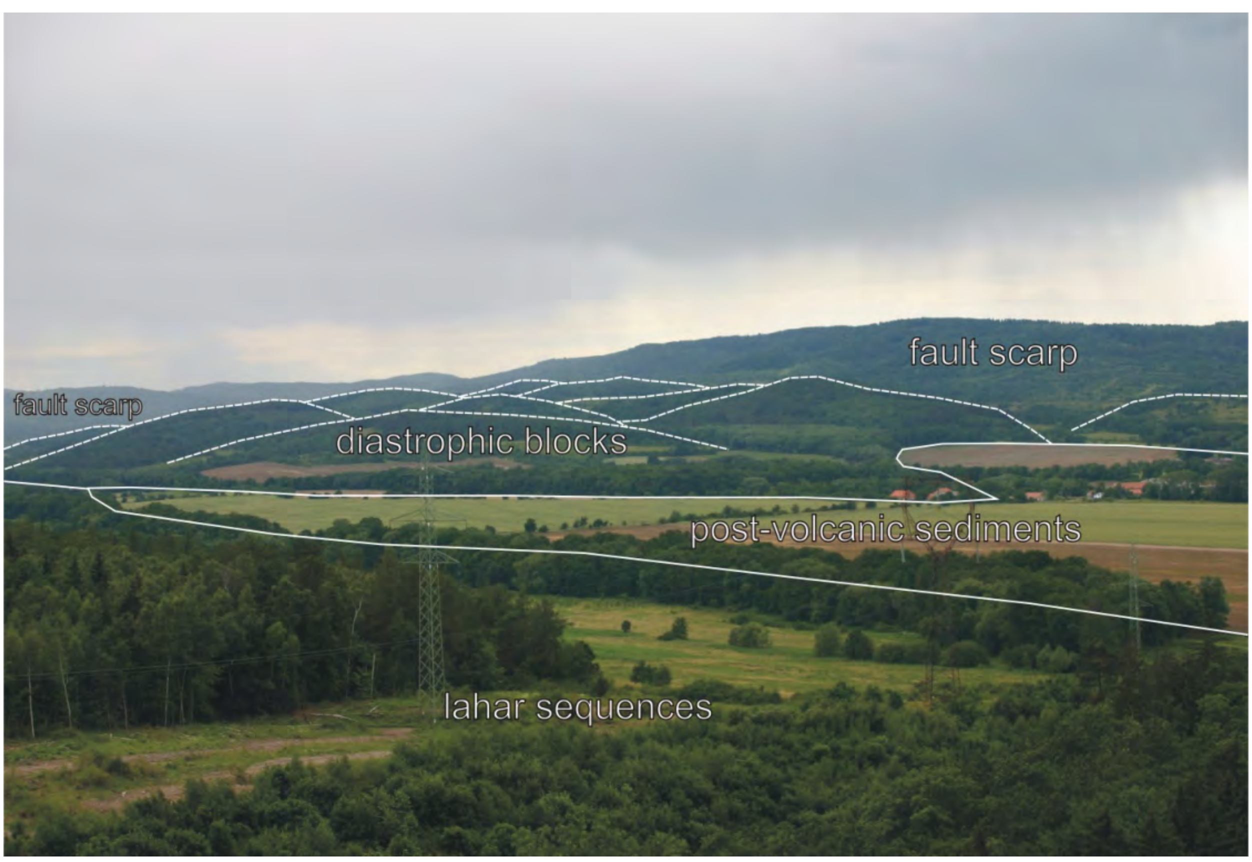

Fig. 15. Hill resembling "hummock" built of lahar deposits on the eastern foothills of the DHVC.

The landscape on the eastern foothills exhibits hummocky-like relief of debris avalanche deposits. However, each "hummock" is stratified and consists of several lahar units (V) and this morphology can be explained as being a result of erosion of a large lahar-based alluvial fan, where the erosion is controlled by the geometry of the lahar-lobes. In contrast to the other lithologies, flat passes are the most frequent morphometric features of the lahars (the majority is also the median in this particular case). These also have the lowest variety of morphometric features of all the studied formations.

Sharp and steep (> 15°) slopes (channels, ridges) correspond to fault scarps (VII). The original steeply inclined planes were affected by erosion and transformed to set of parallel channels and ridges running down the slopes. The fault-scarps observed in the morphology correspond well to important regional faults described for the DHVC basement (e.g., Valenta et al. 2011). The fault scarps are locally associated with areas dominated with large boulders – diastrophic blocks (VI), resulting from local gravity instabilities along the fault scarps. The diastrophic blocks exhibit morphology dominated by steep channels and ridges. We assume that peak classes will dominate in this type of morphology if we use a lower resolution grid.

5. Conclusion

At the present time, DEM's are type of information that is available for much of the globe (SRTM DEM: 90-m spatial resolution, ASTER DEM: 30-m spatial resolution). Slope-dependent morphometry proved to be an efficient and low-cost method that provided unique and valuable information that could not be gathered by any of the field-based methods, especially in terrains with dense vegetation and lacking outcrops. Use of this method permits classification of large formations and algorithmic parameterization facilitates the creation of maps at a different level of generalization. The four morphometric parameters (e.g., slope, cross-sectional curvature, maximum and minimum curvature) led to description of the landforms as ridge, plane, channel, peak, and pass. Additional matrix transformation combining the depicted morphometric parameters with defined slope classes (very low to very high slope) enhanced differences in the rocks based on their geotechnical properties (e.g., rock strength, degree of weathering) and enabled finer sub-level classification which, in combination with the available geological information, allowed us to delineate major geomorphological units for the studied areas, the Conchagua volcano and Doupovské hory Volcanic Complex (DHVC). Due to the exogenic and endogenic processes volcanoes can be quite frequently characterized with high dynamics and slope instability (Kopačková & Šebesta, 2007). As our results combine the relief parameters together with the physical properties of the rocks, they can be further utilized for delineating hazard zones prone to landslides.

Slope-dependent morphometric analysis clearly separates areas of distinct lithologies, as these produce different morphologies. The histograms of morphometric classes may identify, whether the studied area is dominated by erosion or by sedimentation. Additionally, areas of rocks with similar properties can be compared in terms of relative age, as the older ones are affected by erosion more intensively.

The morphometric analysis contributed in geological research of the Conchagua Volcano. Field geological mapping was insufficient for precise definition of lithological boundaries. The boundary lines were improved using morphometric analysis as individual lithologies displayed significantly distinct morphologies. Specific morphologies were observed in the

Doupovské hory Volcanic Complex for lahar sequences and diastrophic blocs bordering fault scarps.

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Phone: +86-21-62489820
Fax: +86-21-62489821